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AN ANALYSIS OF RADIO NAVIGATION SENSOR ACCURACIES ASSOCIATED WI--ETC(U)
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AN ANALYSIS OF RADIO NAVIGATION SENSOR ACCURACIES ASSOCIATED WITH AREA NAVIGATION (RNAV)

NATIONAL AVIATION FACILITIES EXPERIMENTAL CENTER
ATLANTIC CITY, NEW JERSEY

FEBRUARY 1977

Report No. FAA-RD-76-113

AN ANALYSIS OF RADIO NAVIGATION SENSOR ACCURACIES ASSOCIATED WITH AREA NAVIGATION (RNAV)

Robert H. Pursel

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16. Abstract

Flight test data gathered during a series of RNAV flight tests at the National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, New Jersey, are presented. The report concentrates on the radio navigation sensor errors and the resulting errors in position determination that are inherent in area navigation (RNAV) operation in the terminal area. Statistical data as well as distributions of the errors are presented. One-standard deviations of 1.5° for very high frequency omnidirectional radio range (VOR) and 0.094 nautical mile for distance measuring equipment (DME) were computed from the flight test data. These statistics represent combined ground and airborne sensor errors.

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INTRODUCTION

PURPOSE.

The data presented in this report were derived from one of a series of planned flight tests the purposes of which were to investigate 2D, 3D, and 4D area navigation (RNAV) concepts, procedures, and accuracies. The data derived from these tests will be used to establish minimum operational characteristics (MOC) and to determine the impact of RNAV on the air traffic control (ATC) system.

BACKGROUND.

A Federal Aviation Administration (FAA) Industry task force was established to define how to implement RNAV in the National Airspace System (NAS) in an orderly manner, while at the same time, identifying the payoffs to the ATC system and users. A report, entitled "Application of Area Navigation in the National Airspace System," was published in February 1973. This report defined the way in which RNAV would be implemented in the NAS and detailed an action plan which included substantial research and development efforts. As part of this effort, the National Aviation Facilities Experimental Center (NAFEC) has recently conducted flight tests of a sophisticated airline-quality RNAV system to investigate system accuracies and resultant airspace requirements, as well as various operational capabilities. The results of these flight tests were reported under report number FAA-RD-76-32, "A Flight Investigation of System Accuracies and Operational Capabilities of an Air Transport Area Navigation System," by Robert H. Pursel and Jack D. Edmonds. It was felt, however, that certain data obtained from these flight tests, although covered briefly in the previously mentioned report, required separate and expanded treatment. It is the purpose of this report to do just that, concentrating on the raw sensor errors that were obtained during the course of the flight tests. This report is being issued as an interim report. Data from other planned flight tests will subsequently be combined with the data presented in this report, and a final report will be issued.

DISCUSSION

DESCRIPTION OF EQUIPMENT.

The RNAV equipment used for these tests was the Collins Radio ANS-70A system. The system conforms to Aeronautical Radio Incorporated (ARINC) characteristic 582-4, "Mark 2 Air Transport Area Navigation System." Radio sensors used with the RNAV equipment were as follows:

Distance Measuring Equipment (DME)
- Collins Radio 860E-3
- King Radio KDM-7000

Very High Frequency Omnidirectional Radio Range (VOR)
Collins 51RV-2B
Bendix RNA-26C

Both DME's conform to ARINC characteristics 568. The analog outputs of the DME's provided range information to the RNAV equipment, while the digital outputs were routed to a digital instrumentation system for recording purposes.

Both VOR's were modified to provide continuous bearing-to-station information. The modification was a standard field modification to provide four-wire sine-cosine bearing outputs. Work was accomplished, as per Collins Service Bulletin No. 22, for the 51RV-2B and Bendix Mod. 6 (preliminary) for the RNA-26C. The sine-cosine bearing outputs provided bearing information to both the RNAV equipment and the instrumentation system.

For a further description of the RNAV system, including interconnect drawings and photographs, the reader is referred to report FAA-RD-76-32.

EQUIPMENT CALIBRATIONS.

Prior to the start of flight tests, both VOR's and both DME's were calibrated to establish airborne equipment errors. VOR's were checked at 30° intervals from 0° to 330° with a radiofrequency (RF) input level of 100 microvolts. DME's were checked at 5 nautical mile (nmi) intervals from 0 to 150 nmi. Table 1 summarizes the results. No correction factors were applied to the data, because the checks indicated the equipments were within the manufacturer's specifications and therefore represented typical errors in VOR and DME airborne equipment of airline quality.

TABLE 1. AIRBORNE SENSOR CALIBRATION DATA

	Mean	One Standard Deviation
VOR 1	-0.2°	0.4°
VOR 2	0.04°	0.3°
DME 1	0.01 nmi	0.02 nmi
DME 2	-0.06 nmi	0.02 nmi

FLIGHT TESTS.

A series of 68 flights were flown in the local airspace around NAFEC. Three preplanned routes were utilized for the flight tests. Each route was a "round robin" out of NAFEC which was formed by a Standard Instrument Departure (SID), a transition segment, and a Standard Terminal Arrival Route (STAR). Scenarios were utilized to exercise various operational features of the RNAV system by providing what might be typical ATC instructions to the pilot. A more detailed description of the flight tests is contained in Report FAA-RD-76-32.

During the majority of these flights, the autotune feature of the Collins ANS-70A RNAV system was allowed to select and tune the VOR and DME stations which were used for navigation. The station selection procedure is a computer-controlled function, which uses an algorithm to select the most desirable stations from those which are available in the geographical area of aircraft operation. Table 2 presents a list of the stations that were selected by the autotune feature of the RNAV system during the flight tests at NAFEC. The VOR and DME errors and distributions contained in this report were obtained from this data base.

DATA COLLECTION.

AIRBORNE. A mixture of analog, digital, and discrete signals was recorded on a digital incremental recorder at a 2-hertz (Hz) rate throughout the flights. The signals were conditioned and multiplexed by a data acquistion system which was designed and fabricated at NAFEC. A complete list of the parameters recorded is presented in report FAA-RD-76-32.

GROUND. Ground-based data were obtained from NAFEC's Extended Area Instrumentation Radar (EAIR). EAIR is a precision, C-band tracking radar which has a maximum tracking distance of 190 nmi when operated in the beacon tracking mode (all flights were tracked in beacon tracking mode). Digital output data consisting of slant range, azimuth angle, elevation angle, and realtime are recorded on magnetic tape at a 10-Hz rate. Analog track data in X-Y, X-H coordinates are recorded in realtime on 30-inch plot paper. Accuracy of the system is 0.2 milliradian in azimuth and elevation and a root-mean-square (RMS) range error not exceeding 20 yards at 3,000 yard/second range rate.

OBSERVER. Observer data logs were used by the flight test observer to record information pertinent to the flight.

DATA ANALYSIS.

The first step in the data analysis process was to time-merge the ground radar tracking data with the data collected by the airborne data collection system. With this completed, all the raw data necessary to calculate error values were contained on one magnetic tape for each data flight. DME error was defined as: DME ERROR = SENSED RANGE - ACTUAL RANGE. VOR error was defined as: VOR ERROR = SENSED BEARING - ACTUAL BEARING.

These error values, along with other error quantities defining the RNAV system operation, were calculated from the time-merged data tape and placed on another magnetic tape. A separate tape was generated for each flight. These tapes were then used for all subsequent analysis. Full details on the data analysis and error calculations are contained in report FAA-RD-76-32.

TABLE 2. STATIONS USED IN SENSOR ERROR DATA BASE

Frequency (MHz)	Identifier	Location
108.6	ACY	Atlantic City, N.J.
108.2	ARD	Yardley, Pa.
112.6	ATR	Waterloo, Del.
115.4	COL	Colts Neck, N.J.
113.4	CYN	Coyle, N.J.
111.2	DPK	Deer Park, N.Y.
117.9	EMI	Westminster, Md.
111.4	ENO	Kenton, Del.
114.0	EWT	New Castle, Del.
113.6	HTO	Hampton, N.Y.
115.9	JFK	J. F. Kennedy, N.Y.
115.2	MIV	Millville, N.J.
113.2	MXE	Modena, Pa
112.8	OOD	Woodstown, N.J.
113.7	OTT	Nottingham, Md
117.6	PXT	Patuxent, Md.
113.8	RBV	Robbinsville, N.J.
114.1	RIC	Richmond, Va.
112.9	SBJ	Solberg, N.J.
114.5	SBY	Salisbury, Md.
114.8	SIE	Sea Isle, N.J.
112.4	SWL	Snow Hill, Md.

TEST RESULTS

VOR AND DME ERRORS AND ERROR DISTRIBUTIONS.

Data in the form of VOR errors and DME errors were used to calculate means and standard deviations. Means and standard deviations were calculated for each receiver in each of three altitude bands; 0-5,000 feet, 5,000-10,000 feet, and above 10,000 feet. The purpose was to examine the data for receiver biases and determine any significant difference in the errors associated with the different altitude bands. DME data are presented in table 3, while VOR data are presented in table 4.

In examining the DME data, it can be seen that for the same altitude interval, the standard deviations are very similar and the differences approach the range resolution of the airborne DME transceiver (0.01 nmi). Within the same altitude interval, the differences in means indicate the small bias error on the number 2 receiver, which was evident in the equipment calibration. Examining the DME data across the three altitude intervals, a slight tendency toward increasing means and standard deviations, with altitude, can be seen.

The VOR data exhibit similar uniformity across both receivers and altitude intervals. There are some differences in the means which are attributable to the bias errors of the individual stations.

Based on the uniformity of both the DME and VOR data, the data were pooled both across receivers and altitude intervals. Table 5 presents the results of the pooled data. Histograms of the pooled DME and VOR data are presented in figures 1 and 2, respectively. A normal curve is fitted to the data in each case. As can be seen, each of the distributions exhibit a relatively high peak compared to a normal distribution; therefore, the distributions are said to be leptokurtic.

To examine the DME data more closely, the data were entered into a stepwise multiple regression. Stepwise multiple regression is a statistical technique for analyzing a relationship between a dependent variable and a set of independent variables, and for selecting the independent variables in the order of their importance. The dependent variable in this case was DME error, while the independent variables were distance to station (DME distance) and aircraft altitude.

Because of an integer range limitation in the computer used to process the data and the large number of samples processed, the data were divided into four groups so that the number of data points would not exceed the integer range of the computer. Each of the four groups of data was processed, and the results were very similar for all groups.

The results of the regression define the equation for estimating DME error:

$$\text{DME error in nmi} = -0.03 \text{ nmi} - .001 \text{ (DME range in nmi)} - .005 \text{ (Altitude in nmi)}$$

TABLE 3. TOTAL DME ERRORS

Altitude (feet)	No. 1 Mean (nmi)	No. 1 One Standard Deviation (nmi)	No. 1 Samples	No. 2 Mean (nmi)	No. 2 One Standard Deviation (nmi)	No. 2 Samples
0-5,000	-0.05	0.07	13,295	-0.09	0.06	12,855
5,000-10,000	-0.05	0.07	25,051	-0.09	0.08	24,476
Above 10,000	-0.09	0.11	46,006	-0.14	0.09	37,117

TABLE 4. TOTAL VOR ERRORS

Altitude (feet)	No. 1 Mean (deg)	No. 1 One Standard Deviation (deg)	No. 1 Samples	No. 2 Mean (deg)	No. 2 One Standard Deviation (deg)	No. 2 Samples
0-5,000	-0.3	1.4	4,451	0.3	1.6	4,380
5,000-10,000	0.2	1.3	11,726	0.4	1.3	11,488
Above 10,000	-0.3	1.4	26,937	0.1	1.6	20,302

TABLE 5. POOLED TOTAL VOR AND DME ERRORS

VOR			DME		
Mean (deg)	One Standard Deviation (deg)	Samples	Mean (nmi)	One Standard Deviation (nmi)	Samples
0.01	1.5	79,284	-0.092	0.094	158,800

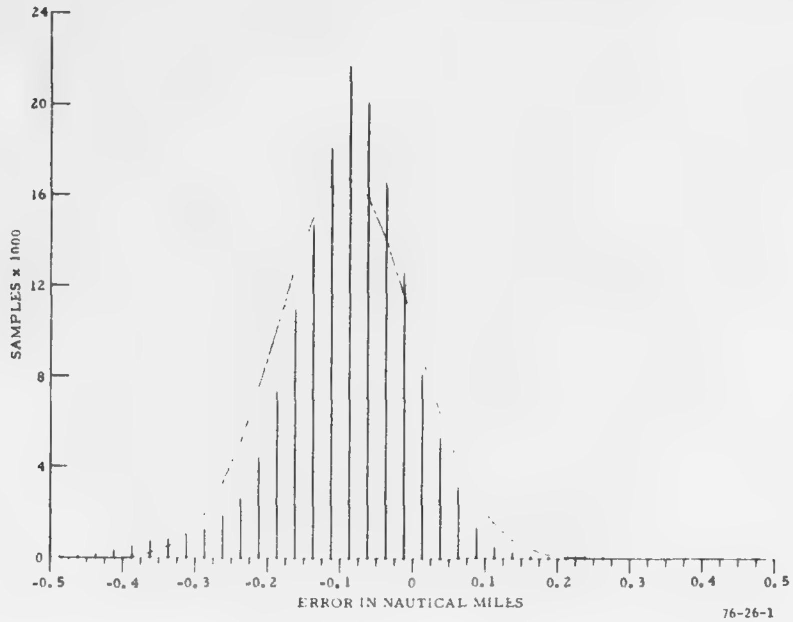


FIGURE 1. DME ERROR DISTRIBUTION

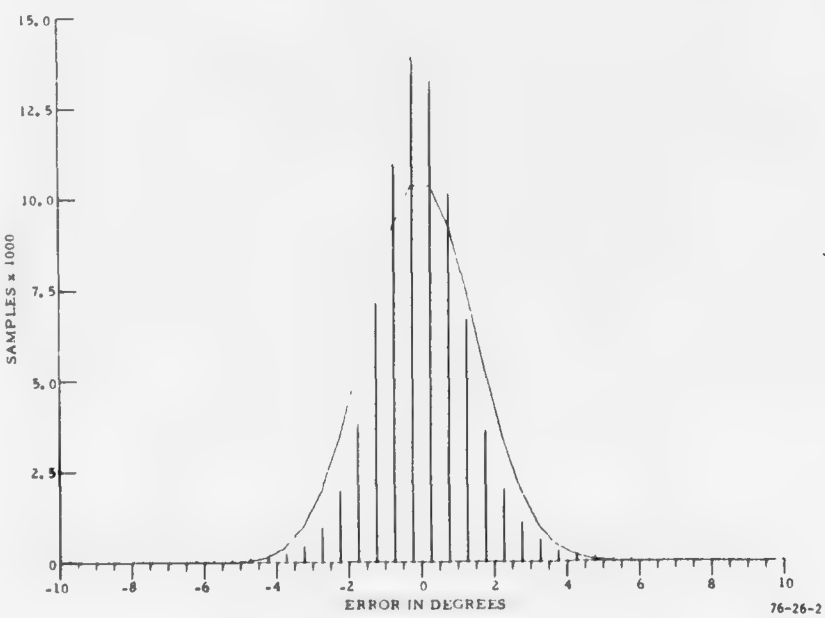


FIGURE 2. VOR ERROR DISTRIBUTION

The resulting equation has a standard error of estimate of approximately 0.1 nmi. The variable which contributed to the largest proportion of sum of squares reduced was DME range. However, with both variables entered into the regression, the cumulative proportion of sum of squares reduced did not exceed 0.3.

VOR/DME NAVIGATION SOLUTION ERRORS AND DISTRIBUTIONS.

Using the flight test data, a position was computed using the measured VOR bearing and measured DME distance. This position was then compared to radar-derived position, and an error value was computed. This error was then resolved into crosstrack and along-track components. Table 6 presents the summary statistics for the position errors for VOR/DME navigation in the terminal area.

TABLE 6. VOR/DME NAVIGATION SOLUTION ERRORS

	Mean (nmi)	One Standard Deviation (nmi)	Number of Samples
V/D Crosstrack Error	0.000	0.327	17,599
V/D Along-Track Error	0.000	0.295	17,599

Figures 3 and 4 present the distributions for VOR/DME navigation solution errors for crosstrack and along-track conditions, respectively. Distributions in both cases are leptokurtic.

Since VOR error is angular in nature, crosstrack and along-track errors in any navigation solution where VOR is used are dependent upon distance from the station. A convenient method to show this relationship is the FAA Advisory Circular 90-45A "tangent point table," in which VOR/DME navigation system errors are broken out as a function of perpendicular tangent point distance and along-track distance (figure 5).

The VOR/DME navigational error data obtained from these RNAV flight tests were organized into intervals defined by the tangent point distance and the along-track distance. This table includes both terminal and enroute data collected on these flights. Two-sigma values for crosstrack and along-track errors were then calculated from the data and entered into an error table of measured 2-sigma accuracies (table 7).

Table 7 is similar in structure to the error tables used in AC 90-45A. The values, however, are based on the measured VOR/DME positional errors and do not include flight technical error (FTE) or RNAV computer error.

There are considerable data missing (indicated by dashes) at the longer tangent point and along-track distances. In an attempt to extrapolate and refine this table, a stepwise multiple regression was run on the data contained in table 7.

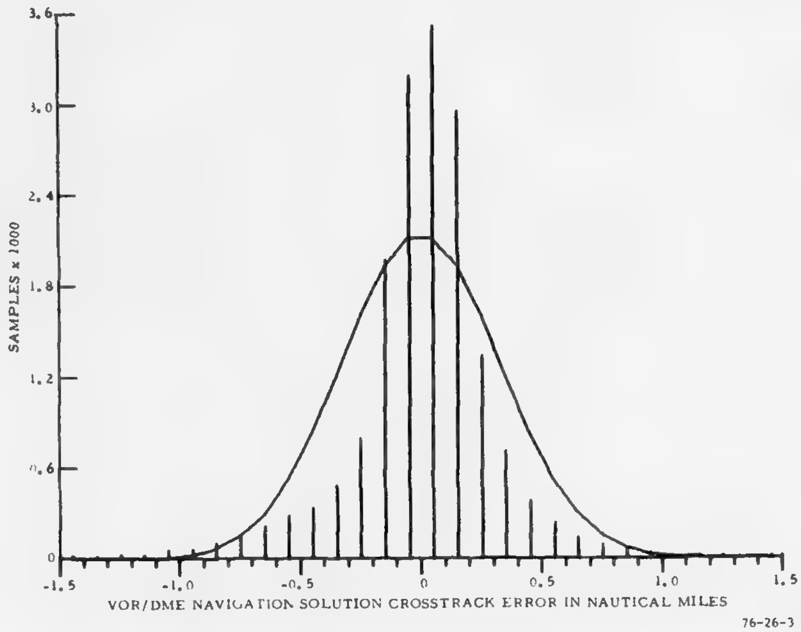


FIGURE 3. VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR DISTRIBUTION

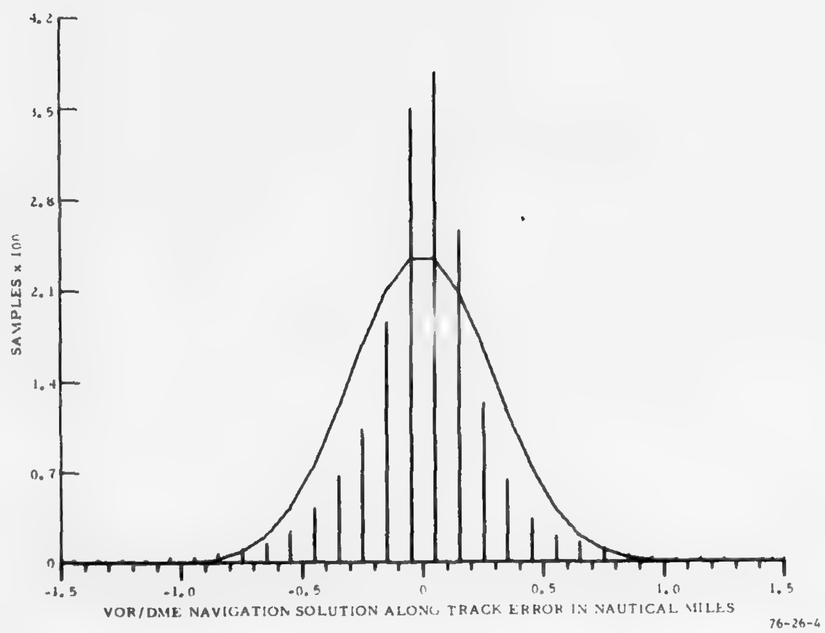


FIGURE 4. VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR DISTRIBUTION

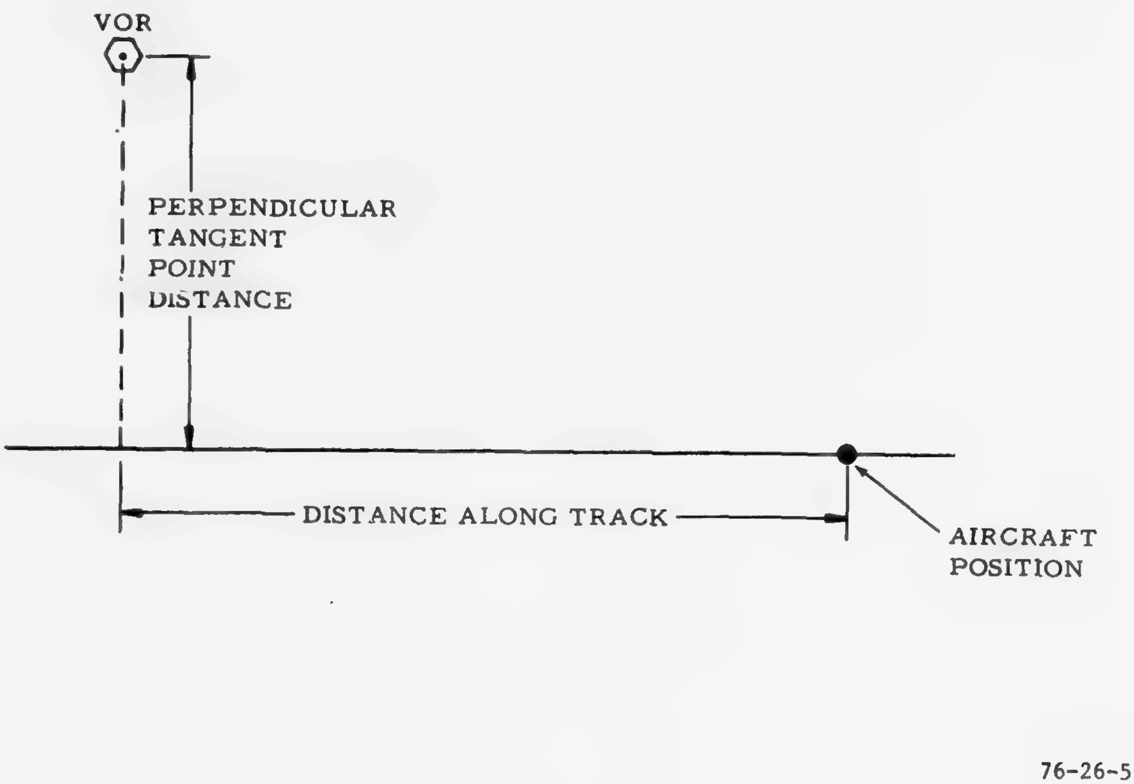


FIGURE 5. ILLUSTRATION OF TANGENT POINT DISTANCE AND ALONG-TRACK DISTANCE

TABLE 7. TANGENT POINT TABLE OF MEASURED 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS

PERPENDICULAR DISTANCE IN NAUTICAL MILES ALONG TRACK FROM TANGENT POINT

PERPENDICULAR DISTANCE IN NAUTICAL MILES FROM TANGENT POINT TO VOR

	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150
0-10(x trk)	0.3	0.6	1.0	1.5	2.3	1.5	2.1	3.2	3.7	4.6	4.3	5.2	3.9	-----	-----
(alg trk)	0.3	0.3	0.3	0.3	0.5	0.3	0.4	0.4	0.4	0.3	0.4	0.1	0.2	-----	-----
10-20(x trk)	0.3	0.6	1.1	2.2	3.1	2.9	2.6	2.7	3.4	3.3	4.4	9.1	---	-----	-----
(alg trk)	0.6	0.6	0.6	0.8	0.9	0.7	0.6	0.5	0.6	0.6	0.6	1.2	---	-----	-----
20-30(x trk)	0.3	1.0	1.2	2.2	2.5	2.7	3.4	4.0	---	---	6.5	7.0	---	-----	-----
(alg trk)	1.2	1.5	1.4	1.6	1.4	1.1	1.5	1.6	---	---	1.3	1.3	---	-----	-----
30-40(x trk)	0.3	0.7	1.5	1.8	1.7	2.0	3.2	2.9	3.3	5.1	---	---	---	-----	-----
(alg trk)	1.7	1.6	2.0	1.7	1.3	1.2	1.5	1.6	1.3	1.9	---	---	---	-----	-----
40-50(x trk)	0.3	0.9	2.0	2.5	3.1	2.0	2.3	2.2	2.7	5.4	3.3	---	---	-----	-----
(alg trk)	2.2	2.5	3.4	2.8	2.4	1.8	1.6	1.4	1.5	3.3	1.6	---	---	-----	-----
50-60(x trk)	0.5	0.7	1.2	0.6	1.4	1.7	---	4.3	5.6	---	---	---	---	-----	-----
(alg trk)	3.3	2.1	2.7	1.0	1.8	1.7	---	3.2	3.5	---	---	---	---	-----	-----
60-70(x trk)	---	---	---	---	---	---	2.3	1.9	2.5	4.5	5.0	---	---	-----	-----
(alg trk)	---	---	---	---	---	---	2.3	1.7	2.1	3.5	3.4	---	---	-----	-----
70-80(x trk)	0.3	1.1	1.6	1.6	1.7	1.6	---	---	---	---	---	---	---	-----	-----
(alg trk)	4.4	4.6	4.5	3.3	2.9	2.7	---	---	---	---	---	---	---	-----	-----
80-90(x trk)	---	---	---	---	---	---	---	---	---	---	---	---	---	-----	-----
(alg trk)	---	---	---	---	---	---	---	---	---	---	---	---	---	-----	-----
90-100(x trk)	0.6	1.1	1.9	2.9	2.6	2.6	---	---	---	---	---	---	---	-----	-----
(alg trk)	6.5	5.7	6.4	8.9	6.6	4.7	---	---	---	---	---	---	---	-----	-----
100-110(x trk)	0.2	---	---	2.4	---	---	---	---	---	---	---	---	---	-----	-----
(alg trk)	6.1	---	---	7.9	---	---	---	---	---	---	---	---	---	-----	-----
110-120(x trk)	0.7	0.7	1.5	2.1	---	---	---	---	---	---	---	---	---	-----	-----
(alg trk)	11.2	7.6	10.1	8.7	---	---	---	---	---	---	---	---	---	-----	-----
120-130(x trk)	---	0.9	---	---	---	---	---	---	---	---	---	---	---	-----	-----
(alg trk)	---	5.9	---	---	---	---	---	---	---	---	---	---	---	-----	-----
130-140(x trk)	---	---	---	---	---	---	---	---	---	---	---	---	---	-----	-----
(alg trk)	---	---	---	---	---	---	---	---	---	---	---	---	---	-----	-----
140-150(x trk)	---	---	---	---	---	---	---	---	---	---	---	---	---	-----	-----
(alg trk)	---	---	---	---	---	---	---	---	---	---	---	---	---	-----	-----

NOTE: THIS TABLE DOES NOT INCLUDE FTE OR RNAV COMPUTER ERRORS

The dependent variable was the 2-sigma value for crosstrack or along-track sensor error, while the independent variables were the tangent point distance and the along-track distance.

The results of the regression for the 2-sigma crosstrack values are presented in table 8. The resulting correlation matrix is presented below. As can be seen, along-track distance (ATD) contributes the largest proportion to the 2-sigma crosstrack error. The contribution of the tangent point distance (TPD) is very negligible. The resulting equation:

2-sigma crosstrack error = -0.187 nmi + 0.044 (ATD) nmi + 0.002 (TDP) nmi,

describes the 2-sigma crosstrack (XTK) error with a standard error of estimate of 0.832 nmi.

CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR REGRESSION

	ATD	TPD	XTK 2 Sigma
ATD	1.00000	-0.35389	0.87177
TDP	-0.35389	1.00000	-0.27341
XTK 2 Sigma	0.87177	-0.27341	1.00000

The results for the 2-sigma along-track regression are similarly presented in table 9, while the resulting correlation matrix is presented in table 10. In this regression, the TPD contributes the largest source of error, while the ATD contribution is nearly negligible. The resulting equation:

2-sigma along-track error = -0.551 nmi + 0.066 (TDP) nmi -0.004 (ATD) nmi,

describes the 2-sigma along-track error with a standard error of estimate of 0.997 nmi.

These two equations were then used to generate a tangent point error table, table 11, for TPD and ATD out to 150 nmi. Some negative values result in the first row of the table for along-track values. This is due to the negative intercept in the along-track regression equation. Obviously, 2-sigma error values cannot be negative. These negative values are underlined in table 11. The table also shows a slightly decreasing 2-sigma along-track error as a function of ATD. For comparison purposes, a theoretical error table was computed, using the error values for VOR and DME that were used in AC 90-45A. These are: VOR ground 1.9°, VOR airborne 3.0°, DME ground 0.1 nmi, DME airborne 3 percent or 0.5 nmi. These error elements are 95-percent probability values. The results are presented in table 12. Note again that this table does not include FTE or RNAV computer errors. Also, the error elements are combined using the AC 90-45A root-sum-square (RSS) method.

TABLE 8. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION CROSSTRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE

Step 1

Variable Entered ..... 1 (ATD)

Sum of Squares Reduced in this Step	185.171		
Proportion Reduced in this Step	0.760		
Cumulative Sum of Squares Reduced	185.171		
Cumulative Proportion Reduced	0.760	of	243.652

For 1 Variable Entered

Multiple Correlation Coefficient	0.872
(Adjusted for D. F.)	0.872
F-Value for Analysis of Variance	272.309
Standard Error of Estimate	0.825
(Adjusted for D. F.)	0.825

Variable Number	Regression Coefficient	Std. Error of Reg. Coeff.	Computed T-Value
1	0.04361	0.00264	16.502
Intercept	-0.04575		

Step 2

Variable Entered ..... 2 (TPD)

Sum of Squares Reduced in this Step	0.343		
Proportion Reduced in this Step	0.001		
Cumulative Sum of Squares Reduced	185.514		
Cumulative Proportion Reduced	0.761	of	243.652

For 2 Variables Entered

Multiple Correlation Coefficient	0.873
(Adjusted for D. F.)	0.871
F-Value for Analysis of Variance	135.617
Standard Error of Estimate	0.827
(Adjusted for D. F.)	0.832

Variable Number	Regression Coefficient	Std. Error of Reg. Coeff.	Computed T-Value
1 (ATD)	0.04432	0.00283	15.640
2 (TPD)	0.00205	0.00290	0.708
Intercept	-0.18716		

TABLE 9. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE

Step 1

Variable Entered ..... 2 (TPD)

Sum of Squares Reduced in this Step	420.908		
Proportion Reduced in this Step	0.832		
Cumulative Sum of Squares Reduced	420.908		
Cumulative Proportion Reduced	0.832	of	505.926

For 1 Variable Entered

Multiple Correlation Coefficient	0.912
(Adjusted for D. F.)	0.912
F-Value for Analysis of Variance	425.770
Standard Error of Estimate	0.994
(Adjusted for D. F.)	0.994

Variable Number	Regression Coefficient	Std. Error of Reg. Coeff.	Computed T-Value
2(TPD)	0.06728	0.00326	20.634
Intercept	-0.86342		

Step 2

Variable Entered ..... 1 (ATD)

Sum of Squares Reduced in this Step	1.524		
Proportion Reduced in this Step	0.003		
Cumulative Sum of Squares Reduced	422.432		
Cumulative Proportion Reduced	0.835	of	505.926

For 2 Variables Entered

Multiple Correlation Coefficient	0.914
(Adjusted for D. F.)	0.913
F-Value for Analysis of Variance	215.027
Standard Error of Estimate	0.991
(Adjusted for D. F.)	0.997

Variable Number	Regression Coefficient	Std. Error of Reg. Coeff.	Computed T-Value
2 (TPD)	0.06575	0.00348	18.920
1 (ATD)	-0.00423	0.00340	-1.246
Intercept	-0.55146		

TABLE 10. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR REGRESSION

	ATD	TPD	ALG TRK 2 Sigma
ATD	1.00000	-0.35389	-0.37412
TPD	-0.35389	1.00000	0.91212
ALG TRK 2 Sigma	-0.37412	0.91212	1.00000

DME/DME NAVIGATION SOLUTION ERRORS AND DISTRIBUTIONS.

A total of 28 RNAV flights were conducted with dual DME used as the radio sensor inputs to the RNAV system. As part of the data analysis, a position was computed from the two DME ranges and was compared to the actual position derived from radar tracking. This provided quantitative data with respect to the DME/DME navigational solution errors.

Statistical data for crosstrack and along-track errors associated with a DME/DME position solution in the terminal area are shown below. Figure 6 is a histogram of the DME/DME crosstrack errors, while figure 7 is a histogram of the DME/DME along-track errors. A normal curve is fitted to each of the histograms.

DME/DME NAVIGATION SOLUTION ERRORS

	Mean	One Standard Deviation	Samples
Crosstrack	0.023 nmi	0.126 nmi	38,693
Along-Track	0.005 nmi	0.155 nmi	38,693

Figure 8 is used to illustrate the geometry of the DME/DME solution and the effect of the included angle between the two DME stations and the aircraft. In these illustrations, the angle θ is formed by the intersection of the lines drawn from the DME stations to the aircraft position. In figure 8A, the angle θ is approximately 90°, and the positions defined by the intersection of the circles of DME range are sharply defined. The ambiguous solution is sufficiently distant from the primary solution so that the ambiguous solution can be discarded by utilizing a VOR bearing or by comparing the two solutions to the approximate position of the aircraft as derived through dead reckoning. Also, small errors in DME range have the least effect in terms of causing errors in the DME/DME solution.

In figure 8B where the angle θ approaches 180° and in figure 8C where the angle θ approaches 0°, the situation is quite different. Neither of the two solutions are sharply defined, and they are close enough to each other so that it may be difficult to discriminate against the ambiguous solution. Also, DME errors will have the largest effect in terms of causing errors in the DME/DME solution.

TABLE 11. TANGENT POINT TABLE OF 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS GENERATED FROM REGRESSION EQUATIONS

DISTANCE IN NAUTICAL MILES ALONG TRACK FROM TANGENT POINT

PERPENDICULAR DISTANCE IN NAUTICAL MILES FROM TANGENT POINT TO VOR

	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150
0-10(x trk)	0.3	0.7	1.2	1.6	2.0	2.5	2.9	3.4	3.8	4.3	4.7	5.2	5.6	6.0	6.5
(alg trk)	0.1	0.0	-0.0	-0.1	-0.1	-0.1	-0.2	-0.2	-0.3	-0.3	-0.4	-0.4	-0.4	-0.5	-0.5
10-20(x trk)	0.3	0.7	1.2	1.6	2.1	2.5	3.0	3.4	3.8	4.3	4.7	5.2	5.6	6.1	6.5
(alg trk)	0.7	0.7	0.6	0.6	0.6	0.5	0.5	0.4	0.4	0.3	0.3	0.3	0.2	0.2	0.1
20-30(x trk)	0.3	0.8	1.2	1.6	2.1	2.5	3.0	3.4	3.9	4.3	4.7	5.2	5.6	6.1	6.5
(alg trk)	1.4	1.3	1.3	1.3	1.2	1.2	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.8	0.8
30-40(x trk)	0.3	0.8	1.2	1.7	2.1	2.6	3.0	3.4	3.9	4.3	4.8	5.2	5.7	6.1	6.5
(alg trk)	2.0	2.0	2.0	1.9	1.9	1.8	1.8	1.7	1.7	1.7	1.6	1.6	1.5	1.5	1.4
40-50(x trk)	0.4	0.8	1.2	1.7	2.1	2.6	3.0	3.5	3.9	4.3	4.8	5.2	5.7	6.1	6.6
(alg trk)	2.7	2.7	2.6	2.6	2.5	2.5	2.4	2.4	2.4	2.3	2.3	2.2	2.3	2.1	2.1
50-60(x trk)	0.4	0.8	1.3	1.7	2.2	2.6	3.0	3.5	3.9	4.4	4.8	5.3	5.7	6.1	6.6
(alg trk)	3.4	3.3	3.3	3.2	3.2	3.1	3.1	3.1	3.0	3.0	2.9	2.9	2.8	2.8	2.8
60-70(x trk)	0.4	0.8	1.3	1.7	2.2	2.6	3.1	3.5	3.9	4.4	4.8	5.3	5.7	6.2	6.6
(alg trk)	4.0	4.0	3.9	3.9	3.8	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.5	3.4
70-80(x trk)	0.4	0.9	1.3	1.7	2.2	2.6	3.1	3.5	4.0	4.4	4.9	5.3	5.7	6.2	6.6
(alg trk)	4.7	4.6	3.6	4.5	4.5	4.5	4.4	4.4	4.3	4.3	4.2	4.2	4.2	4.1	4.1
80-90(x trk)	0.4	0.9	1.3	1.8	2.2	2.7	3.1	3.5	4.0	4.4	4.9	5.3	5.8	6.2	6.6
(alg trk)	5.3	5.3	5.2	5.2	5.2	5.1	5.1	5.0	5.0	4.9	4.9	4.9	4.8	4.8	4.7
90-100(x trk)	0.5	0.9	1.3	1.8	2.2	2.7	3.1	3.6	4.0	4.4	4.9	5.3	5.8	6.2	6.7
(alg trk)	6.0	5.9	5.9	5.9	5.8	5.8	5.7	5.7	5.6	5.6	5.6	5.5	5.5	5.4	5.4
100-110(x trk)	0.5	0.9	1.4	1.8	2.3	2.7	3.1	3.6	4.0	4.5	4.9	5.4	5.8	6.2	6.7
(alg trk)	6.6	6.6	6.6	6.5	6.5	6.4	6.4	6.3	6.3	6.3	6.2	6.2	6.1	6.1	6.0
110-120(x trk)	0.5	0.9	1.4	1.8	2.3	2.7	3.2	3.6	4.0	4.5	4.9	5.4	5.8	6.2	6.7
(alg trk)	7.3	7.3	7.2	7.2	7.1	7.1	7.0	7.0	7.0	6.9	6.9	6.8	6.8	6.7	6.7
120-130(x trk)	0.5	1.0	1.4	1.9	2.3	2.7	3.2	3.6	4.1	4.5	5.0	5.4	5.8	6.3	6.7
(alg trk)	8.0	7.9	7.9	7.8	7.8	7.7	7.7	7.7	7.6	7.6	7.5	7.5	7.4	7.4	7.4
130-140(x trk)	0.5	1.0	1.4	1.9	2.3	2.8	3.2	3.6	4.1	4.5	5.0	5.4	5.9	6.3	6.7
(alg trk)	8.6	8.6	8.5	8.5	8.4	8.4	8.4	8.3	8.3	8.2	8.2	8.1	8.1	8.1	8.0
140-150(x trk)	0.6	1.0	1.5	1.9	2.3	2.8	3.2	3.7	4.1	4.6	5.0	5.4	5.9	6.3	6.8
(alg trk)	9.3	9.2	9.2	9.1	9.1	9.1	9.0	9.0	8.9	8.9	8.8	8.8	8.8	8.7	8.7

NOTE: THIS TABLE DOES NOT INCLUDE FTE OR RNAV COMPUTER ERRORS

TABLE 12. TANGENT POINT TABLE OF 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS USING AC 90-45A 2 SIGMA VALUES FOR VOR AND DME ERRORS

DISTANCE IN NAUTICAL MILES ALONG TRACK FROM TANGENT POINT

PERPENDICULAR DISTANCE IN NAUTICAL MILES FROM TANGENT POINT TO VOR

	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
10(x trk)	0.7	1.3	1.9	2.5	3.1	3.7	4.4	5.0	5.6	6.2	6.8	7.4	8.1	8.7	9.3
(alg trk)	0.7	0.9	1.1	1.4	1.6	1.9	2.2	2.5	2.8	3.1	3.4	3.7	4.0	4.2	4.5
20(x trk)	0.9	1.4	2.0	2.6	3.2	3.8	4.4	5.0	5.6	6.2	6.8	7.5	8.1	8.7	9.3
(alg trk)	1.3	1.4	1.5	1.7	1.9	2.2	2.4	2.7	3.0	3.2	3.5	3.8	4.1	4.4	4.7
30(x trk)	1.1	1.5	2.1	2.6	3.2	3.8	4.4	5.0	5.7	6.3	6.9	7.5	8.1	8.7	9.3
(alg trk)	1.9	2.0	2.1	2.2	2.4	2.6	2.8	3.0	3.3	3.5	3.8	4.1	4.3	4.6	4.9
40(x trk)	1.4	1.7	2.2	2.8	3.3	3.9	4.5	5.1	5.7	6.3	6.9	7.5	8.2	8.8	9.4
(alg trk)	2.5	2.6	2.6	2.8	2.9	3.1	3.3	3.5	3.7	3.9	4.1	4.4	4.6	4.9	5.1
50(x trk)	1.6	1.9	2.4	2.9	3.4	4.0	4.6	5.2	5.8	6.4	7.0	7.6	8.2	8.8	9.4
(alg trk)	3.1	3.2	3.2	3.3	3.4	3.6	3.7	3.9	4.1	4.3	4.5	4.8	5.0	5.2	5.5
60(x trk)	1.9	2.2	2.6	3.1	3.6	4.1	4.7	5.3	5.9	6.5	7.1	7.7	8.3	8.9	9.5
(alg trk)	3.7	3.8	3.8	3.9	4.0	4.1	4.3	4.4	4.6	4.8	5.0	5.2	5.4	5.6	5.8
70(x trk)	2.2	2.4	2.8	3.3	3.7	4.3	4.8	5.4	6.0	6.5	7.1	7.7	8.3	8.9	9.5
(alg trk)	4.4	4.4	4.4	4.5	4.6	4.7	4.8	5.0	5.1	5.3	5.5	5.6	5.8	6.0	6.3
80(x trk)	2.5	2.7	3.0	3.5	3.9	4.4	5.0	5.5	6.1	6.7	7.2	7.8	8.4	9.0	9.6
(alg trk)	5.0	5.0	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.8	6.0	6.1	6.3	6.5	6.7
90(x trk)	2.8	3.0	3.3	3.7	4.1	4.6	5.1	5.6	6.2	6.8	7.3	7.9	8.5	9.1	9.7
(alg trk)	5.6	5.6	5.7	5.7	5.8	5.9	6.0	6.1	6.2	6.3	6.5	6.6	6.8	7.0	7.2
100(x trk)	3.1	3.2	3.5	3.9	4.3	4.8	5.3	5.8	6.3	6.9	7.5	8.0	8.6	9.2	9.8
(alg trk)	6.2	6.2	6.3	6.3	6.4	6.5	6.5	6.7	6.8	6.9	7.0	7.2	7.3	7.5	7.7
110(x trk)	3.4	3.5	3.8	4.1	4.5	5.0	5.5	6.0	6.5	7.0	7.6	8.1	8.7	9.3	9.9
(alg trk)	6.8	6.8	6.9	6.9	7.0	7.1	7.1	7.2	7.3	7.5	7.6	7.7	7.9	8.0	8.2
120(x trk)	3.7	3.8	4.1	4.4	4.8	5.2	5.6	6.1	6.6	7.2	7.7	8.3	8.8	9.4	10.0
(alg trk)	7.4	7.5	7.5	7.5	7.6	7.7	7.7	7.8	7.9	8.0	8.1	8.3	8.4	8.5	8.7
130(x trk)	4.0	4.1	4.3	4.6	5.0	5.4	5.8	6.3	6.8	7.3	7.9	8.4	9.0	9.5	10.1
(alg trk)	8.1	8.1	8.1	8.2	8.2	8.3	8.3	8.4	8.5	8.6	8.7	8.8	9.0	9.1	9.2
140(x trk)	4.2	4.4	4.6	4.9	5.2	5.6	6.0	6.5	7.0	7.5	8.0	8.5	9.1	9.6	10.2
(alg trk)	8.7	8.7	8.7	8.8	8.8	8.9	8.9	9.0	9.1	9.2	9.3	9.4	9.5	9.6	9.8
150(x trk)	4.5	4.7	4.9	5.1	5.5	5.8	6.3	6.7	7.2	7.7	8.2	8.7	9.2	9.8	10.3
(alg trk)	9.3	9.3	9.3	9.4	9.4	9.5	9.5	9.6	9.7	9.8	9.9	10.0	10.1	10.2	10.3

NOTE: THIS TABLE DOES NOT INCLUDE FTE OR RNAV COMPUTER ERRORS

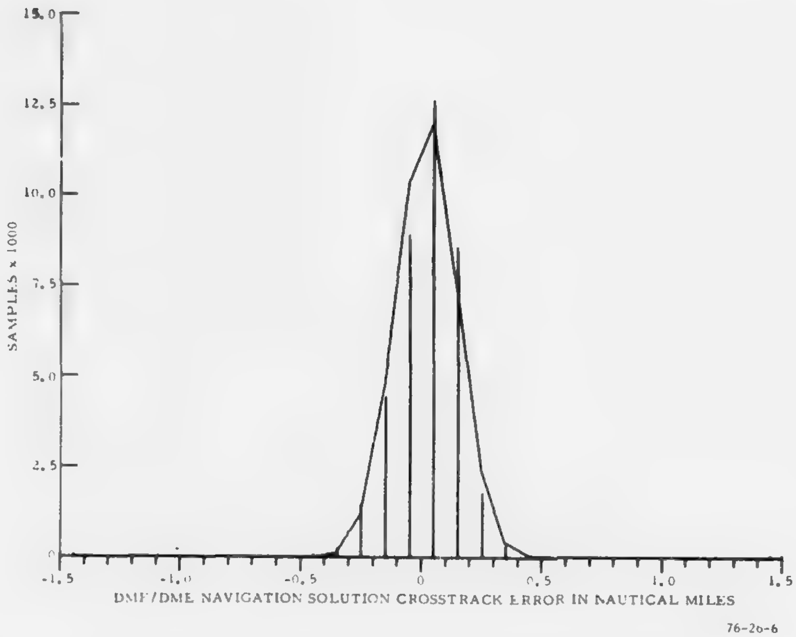


FIGURE 6. DME/DME NAVIGATION SOLUTION CROSSTRACK ERROR DISTRIBUTION

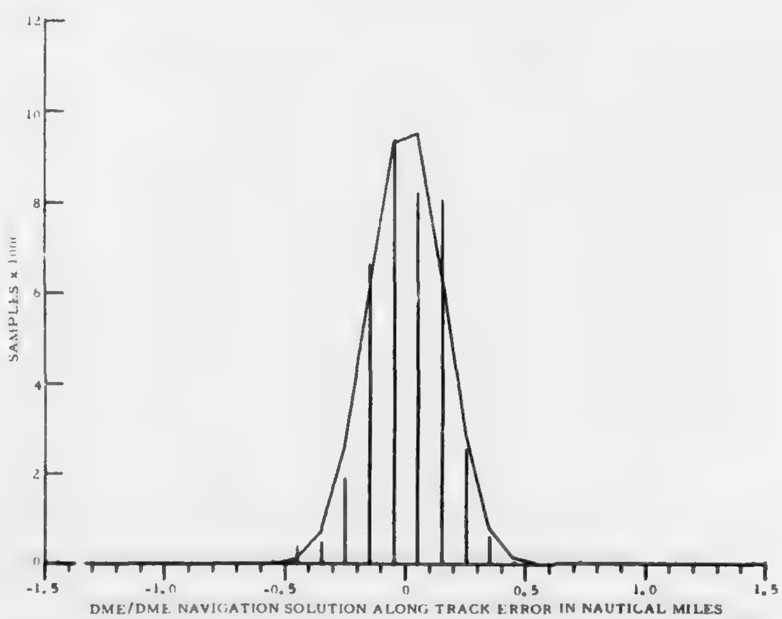
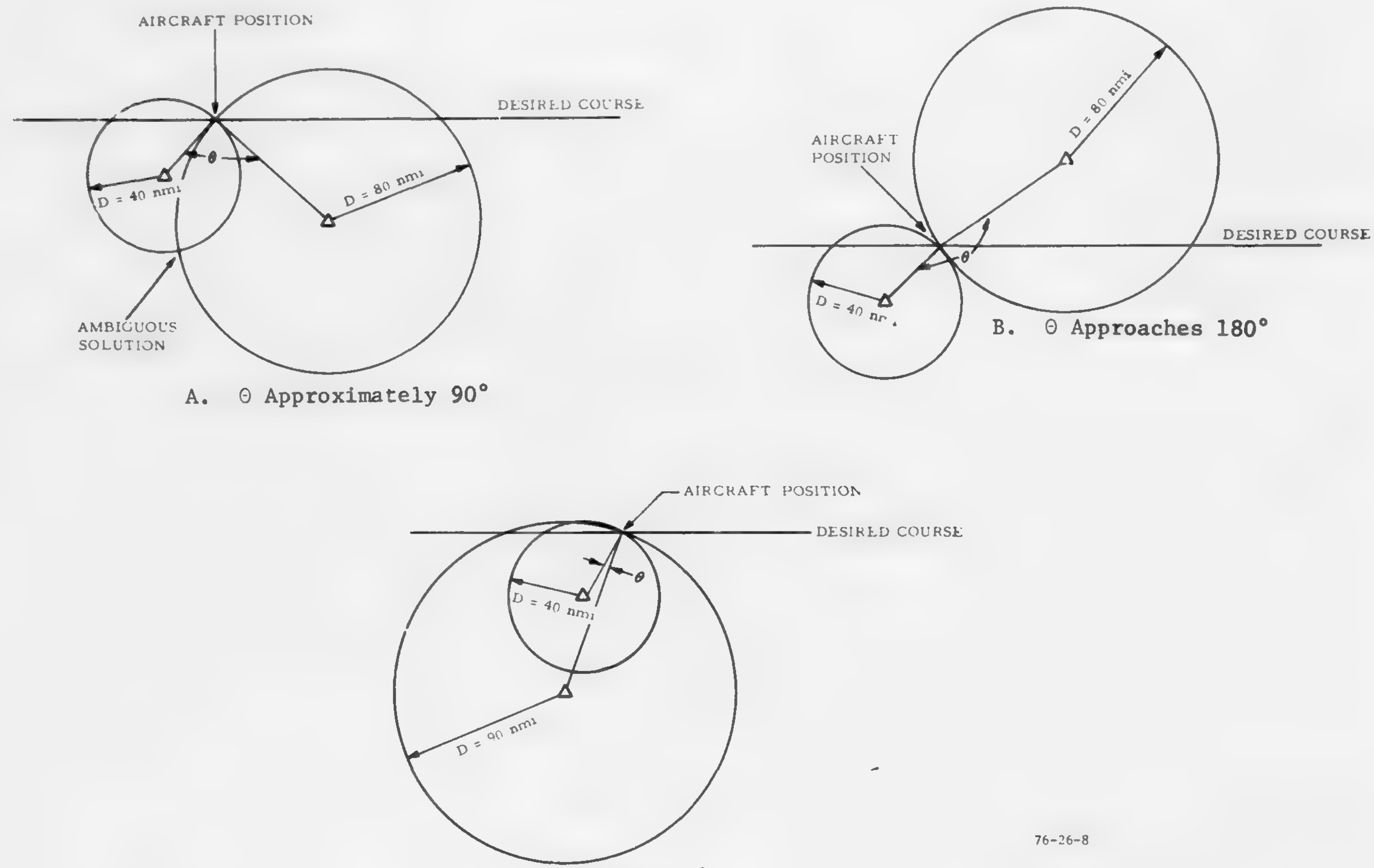


FIGURE 7. DME/DME NAVIGATION SOLUTION ALONG-TRACK ERROR DISTRIBUTION



A. Θ Approximately 90°

B. Θ Approaches 180°

C. Θ Approaches 0°

FIGURE 8. DME/DME NAVIGATION SOLUTION GEOMETRY

In the RNAV system tested, software inhibited the use of DME stations if the included angle formed by the two stations met the criteria 30° >θ >150°. Figures 9 and 10 illustrate the relation between the included angle and the 2-standard-deviation navigation solution error. Solution errors increase at both the upper and lower limits of the included angle. Figure 11 is a histogram of the sampling frequency in relation to the included angle.

RNAV COMPUTER ERRORS AND DISTRIBUTIONS FOR VOR/DME NAVIGATION MODE.

RNAV computer errors in both crosstrack and along-track positions were computed from those flights where VOR/DME was used as the prime navigational mode. These errors represent the differences between the sensed (radio) position and the position as calculated by the RNAV computer. The difference calculated from these two measurements is the generally accepted measure of the RNAV computer error. The reader is reminded, however, that the RNAV system used for these tests was a very sophisticated system which utilized a modified Kalman filter to determine the best estimate of present position from the sensor data available. Because of this, the value for RNAV computer error generally had negative correlation with the value for sensor error (see report FAA-RD-76-32), and therefore reduced the total system error value rather than adding to it. In this case, RNAV computer error could be more properly called "filter complementation", with the term "error" deleted. "RNAV computer error" will still be used, however, because it conforms with the conventions used in AC90-45A and the RNAV Task Force report.

Table 13 presents the statistical data, while figures 12 and 13 are histograms of RNAV computer crosstrack and along-track error, respectively.

TABLE 13. RNAV COMPUTER ERRORS FOR VOR/DME NAVIGATION MODE

	Mean (nmi)	One Standard Deviation (nmi)	Samples
Crosstrack	-0.029	0.311	17,599
Along-Track	0.002	0.286	17,599

RNAV COMPUTER ERRORS AND DISTRIBUTIONS FOR DME/DME NAVIGATION MODE.

RNAV computer errors in both crosstrack and along-track positions were computed from those flights where DME/DME was used as the prime navigational mode. These errors represent the differences between the sensed (radio) position and the position as calculated by the RNAV computer. Table 14 presents the statistical data, while figures 14 and 15 are histograms of RNAV computer crosstrack and along-track error, respectively.

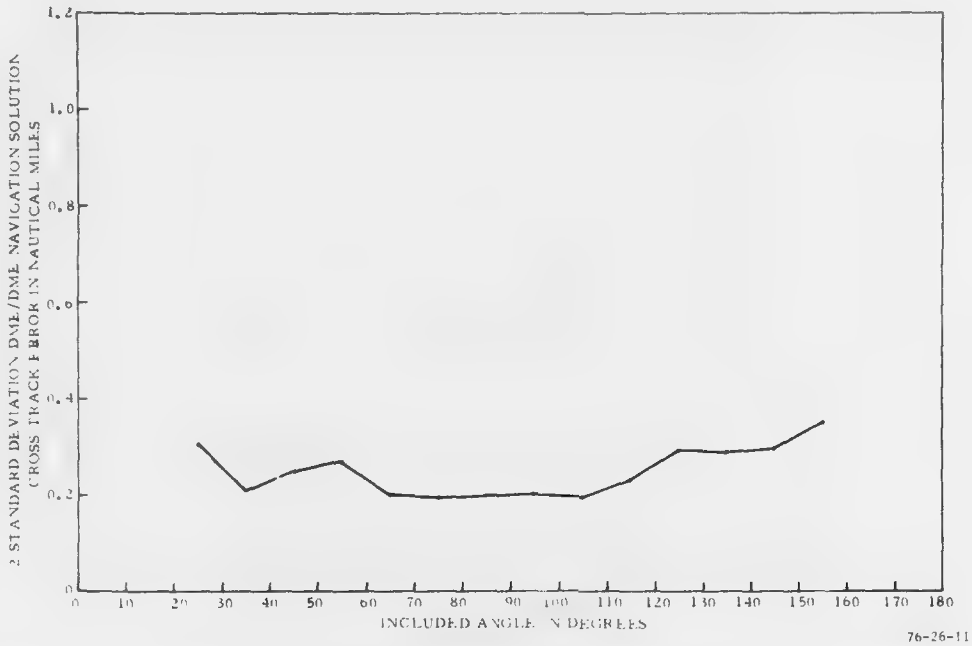


FIGURE 9. DME/DME NAVIGATION SOLUTION 2-SIGMA CROSSTRACK ERRORS AS A FUNCTION OF INCLUDED ANGLE

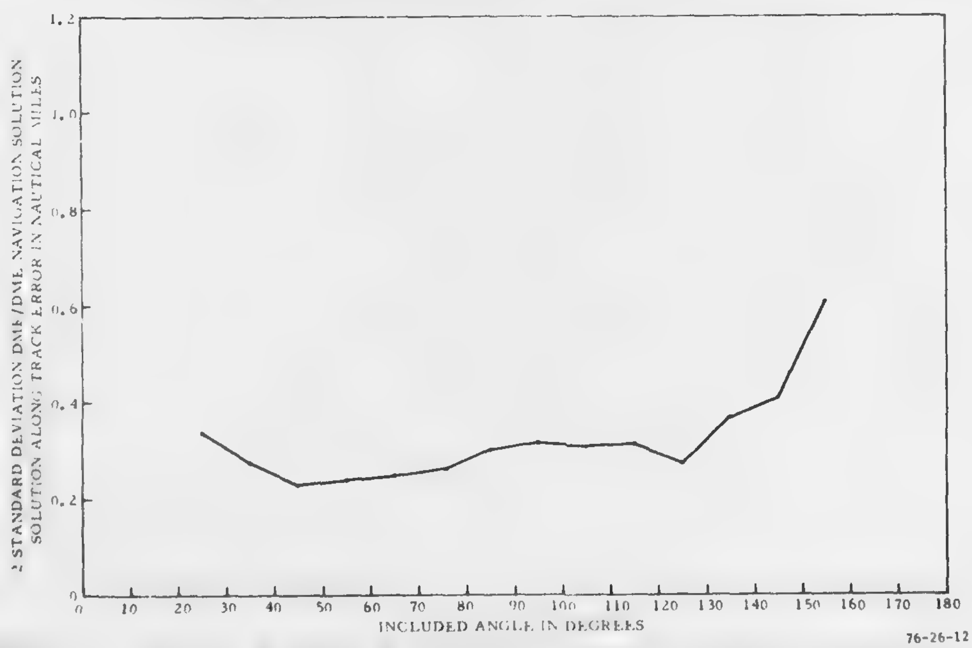


FIGURE 10. DME/DME NAVIGATION SOLUTION 2-SIGMA ALONG-TRACK ERRORS AS A FUNCTION OF INCLUDED ANGLE

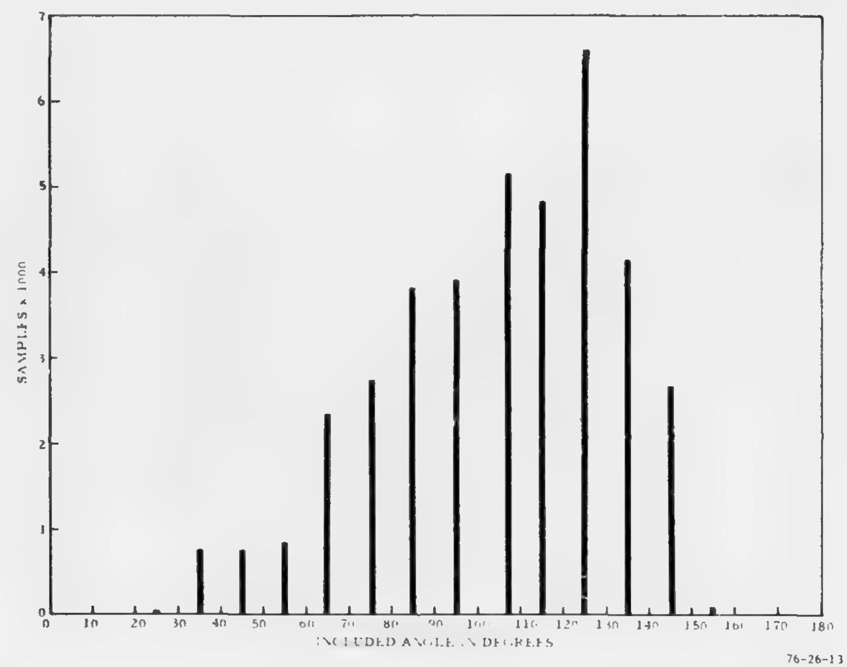


FIGURE 11. DISTRIBUTION OF DME/DME STATION SELECTION AS A FUNCTION OF INCLUDED ANGLE

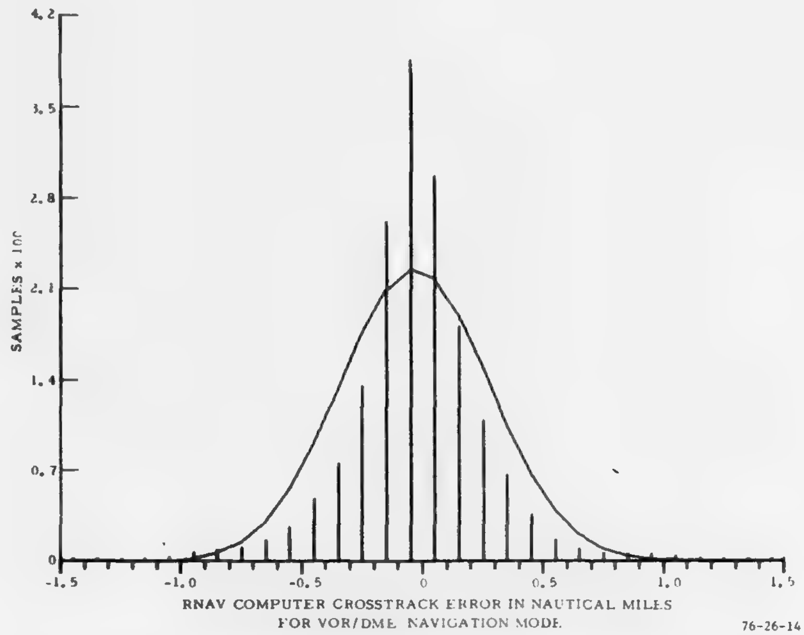


FIGURE 12. DISTRIBUTION OF RNAV COMPUTER CROSSTRACK ERRORS FOR VOR/DME NAVIGATION MODE

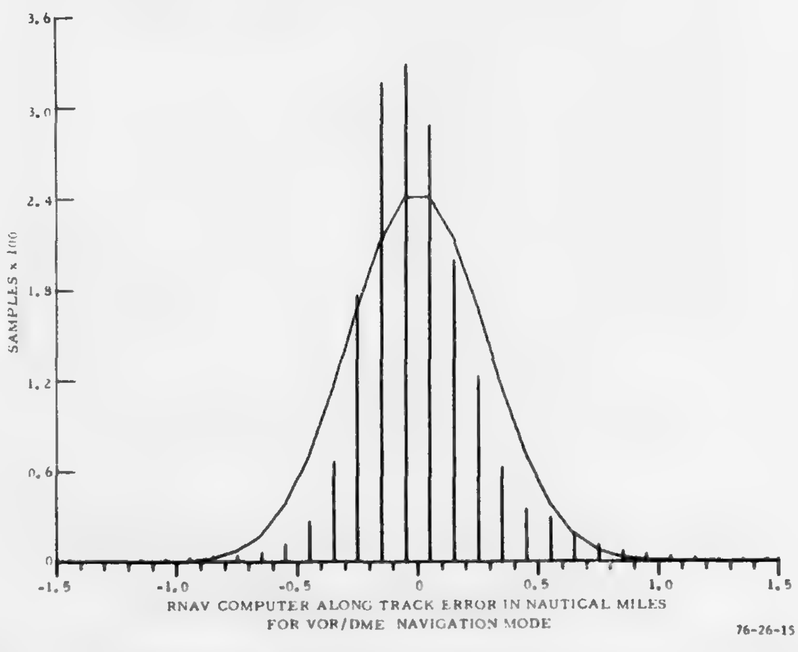


FIGURE 13. DISTRIBUTION OF RNAV COMPUTER ALONG-TRACK ERRORS FOR VOR/DME NAVIGATION MODE

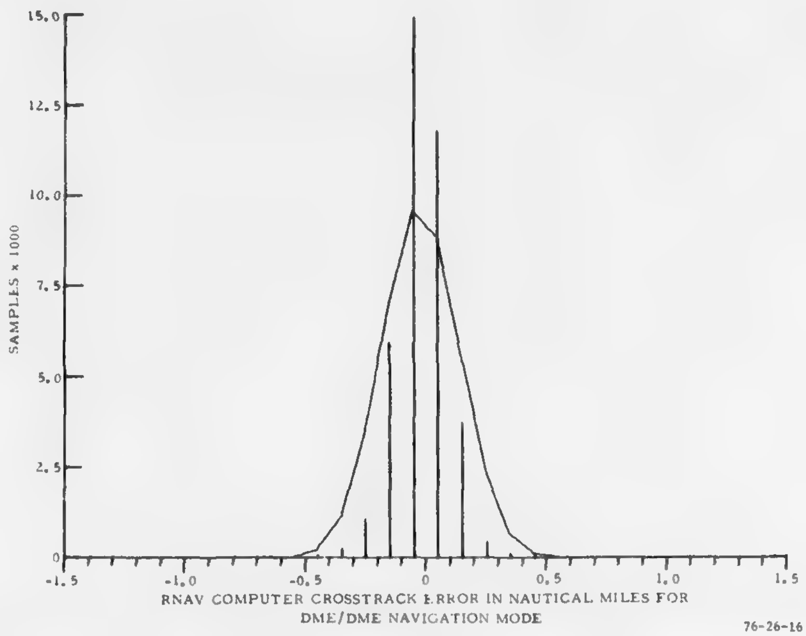


FIGURE 14. DISTRIBUTION OF RNAV COMPUTER CROSSTRACK ERRORS FOR DME/DME NAVIGATION MODE

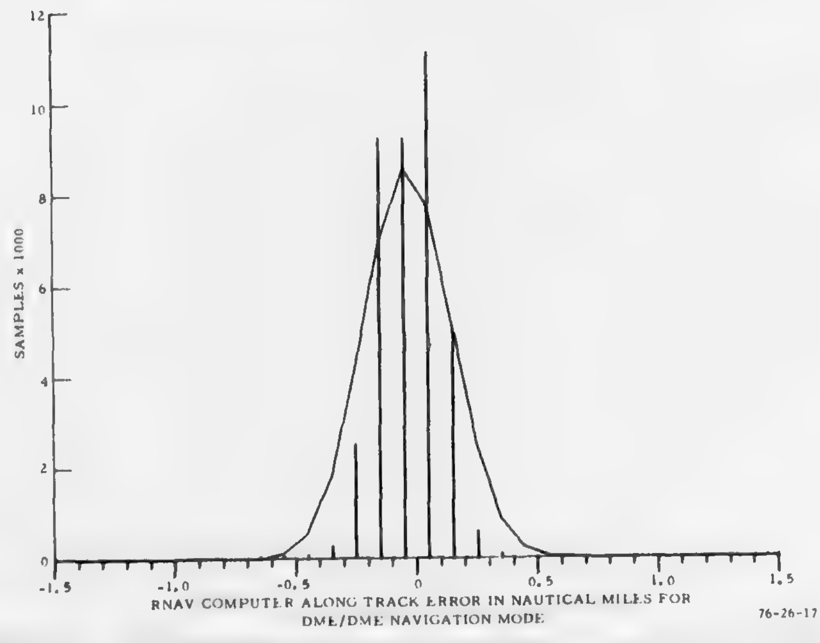


FIGURE 15. DISTRIBUTION OF RNAV COMPUTER ALONG-TRACK ERRORS FOR DME/DME NAVIGATION MODE

TABLE 14. RNAV COMPUTER ERRORS FOR DME/DME NAVIGATION MODE

	Mean (nmi)	One Standard Deviation (nmi)	Samples
Crosstrack	-0.019	0.159	38,693
Along-Track	-0.033	0.180	38,693

FLIGHT TECHNICAL ERROR DISTRIBUTIONS FOR AUTOPILOT-COUPLED OPERATIONS.

Autopilot FTE crosstrack data from a series of 14 autopilot-coupled flights were statistical tabulated. The data include both terminal and approach FTE. Data were taken over steady state route conditions and do not include turn data.

Table 15 enumerates the results of the statistical tabulation, while figure 16 presents a histogram of the FTE crosstrack data.

TABLE 15. AUTOPILOT FTE CROSSTRACK DATA

Mean (nmi)	One Standard Deviation (nmi)	No. of Samples
-0.004	0.09	15,474

FLIGHT TECHNICAL ERROR DISTRIBUTIONS FOR MANUAL OPERATIONS.

Manual FTE crosstrack data from a series of 14 RNAV flights were statistically tabulated. The data include both terminal and approach FTE. Data were taken over steady state route conditions and do not include turn data. Table 16 enumerates the results of the statistical tabulations, while figure 17 presents a histogram of the FTE crosstrack data.

TABLE 16. MANUAL FTE CROSSTRACK DATA

Mean (nmi)	One Standard Deviation (nmi)	No. of Samples
-0.042	0.124	14,171

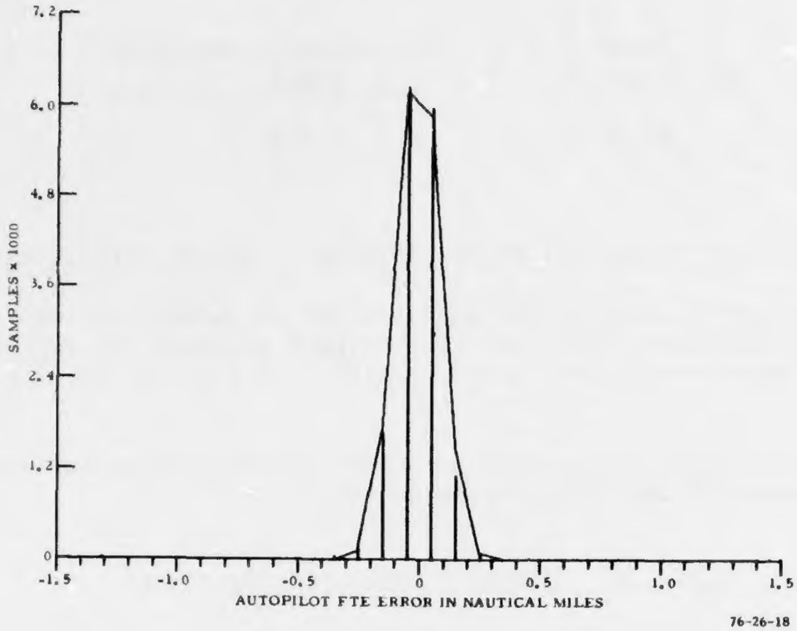


FIGURE 16. DISTRIBUTION OF FLIGHT TECHNICAL ERROR FOR AUTOPILOT-COUPLED OPERATIONS

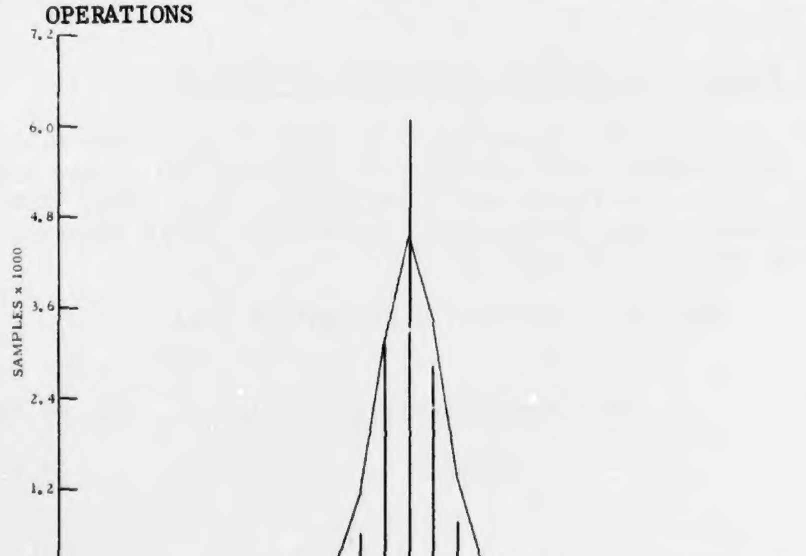


FIGURE 19. DISTRIBUTION OF FLIGHT TECHNICAL ERROR FOR MANUAL OPERATIONS

FIGURE 17. DISTRIBUTION OF FLIGHT TECHNICAL ERROR FOR MANUAL OPERATIONS

SUMMARY OF RESULTS

1. Combined ground and airborne sensor errors for DME resulted in a mean of -0.092 nmi with a one standard deviation of 0.094 nmi.

2. Combined ground and airborne sensor errors for VOR resulted in a mean of 0.01° with a one standard deviation of 1.5°.

3. The distributions of both DME and VOR errors were leptokurtic.

4. Navigation solutions in the terminal area using VOR/DME radio information resulted in positional errors as follows:

	Mean (nmi)	One Standard Deviation (nmi)
Crosstrack	0.000	0.327
Along-Track	0.000	0.295

5. The distributions of both crosstrack and along-track VOR/DME navigation solution errors were leptokurtic.

6. Navigation solutions in the terminal area using DME/DME radio information resulted in positional errors as follows:

	Mean (nmi)	One Standard Deviation (nmi)
Crosstrack	0.023	0.126
Along-Track	0.005	0.155

7. RNAV computer errors (filter complementation) in the VOR/DME navigation mode in the terminal area were as follows:

	Mean (nmi)	One Standard Deviation (nmi)
Crosstrack	-0.029	0.311
Along-Track	0.002	0.286

8. RNAV computer errors (filter complementation) in the DME/DME navigation mode in the terminal area were as follows:

	Mean (nmi)	One Standard Deviation (nmi)
Crosstrack	-0.019	0.159
Along-Track	-0.033	0.180

9. Flight technical errors for autopilot-coupled operations in the terminal area were as follows:

	Mean (nmi)	One Standard Deviation (nmi)
Crosstrack	-0.004	0.09

10. Flight technical errors for manual operations in the terminal area were as follows:

	Mean (nmi)	One Standard Deviation (nmi)
Crosstrack	-0.042	0.124

CONCLUSIONS

1. The 2-sigma value of 3.0° for combined ground and airborne VOR error measured during these flights compares favorably with the 2-sigma value of 3.55° (±1.9 ground and ±3.0 airborne combined using root-sum-square) used in AC 90-45A.

2. DME errors (combined ground and airborne) measured were much smaller than the AC 90-45A budget. Combined ground and airborne errors were estimated at 0.1 percent of the DME range. The low error values are presumed to be a result of the high-quality DME airborne receivers used for these tests.

3. A comparison between a tangent point table calculated from measured VOR and DME errors and one calculated from the VOR and DME error budget used in AC 90-45A showed smaller crosstrack and along-track 2-sigma errors in the table calculated from measured VOR and DME errors. The reduction is most evident where DME is the major error contributor.

4. The terminal area crosstrack and along-track errors for a VOR/DME navigation solution were at least two times as large as the corresponding errors for a DME/DME navigation solution.